Remote Sensing of Bathymetry: An Investigation into the Effect of Bottom Reflectance on Passive Upwelling Spectral Irradiance

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ABSTRACT

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A spectral ratio technique was used to identify the effect of bottom composition on the upwelling spectral irradiance. When water depths were less than the secchi disc depth the bottom reflectance could be observed in spectral ratio variations with suspended load. The ratio method could not distinguish between a mud or sand bottom since these bottom compositions showed the same shape of spectral bottom reflectance. The inshore water area off Liscomb, Nova Scotia, was thought to be optically typical of many sections of the coastlines. The methods of data recording, strategy and water analysis used in the survey were all at their respective error limits and would need to be modified or upgraded before any further quantitative scientific work could be conducted.

RÉSUMÉ

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L'auteur s'est servi d'une technique par coefficient spectral pour déterminer l'effet de la composition du fond sur l'irradiation spectrale de remontée. Lorsque les prodondeurs d'eau étaient inférieures à la profondeur du disque de Secchi, la réflexion du fond pouvait être observée dans des variations du coefficient spectral par rapport à la charge en suspension. La méthode par coefficient n'a pas permis de faire la distinction entre un fond vaseux et un fond sableux puisque la composition de chacun de ces fonds présentait la même courbe de réflexion spectrale du fond. On pensait que la zone marine au large de Liscomb (Nova Scotia) était optiquement typique de nombreux secteurs du littoral. Les modes de relevé des données, la stratergie et l'analyse de l'eau employés dans le relevé ont tous été poussés à leur limite respective d'erreur et ils devraient être modifiés ou améliorés avant que de plus amples travaux scientifiques de quantification ne puissent être menés.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
LIST OF TABLES	v
LIST OF FIGURES	vi
INTRODUCTION	1
FIELD LOCATION	1
DATA COLLECTION	3
OBSERVATIONAL MEASUREMENTS	4
LOCAL OPTICAL CHARACTERISTICS	5
WATER QUALITY AND BOTTOM TYPE	6
ERRORS OF MEASUREMENTS	9
CONCLUSIONS	10
RECOMMENDATIONS	11
REFERENCES	21

LIST OF TABLES

Page

Table 1. Spectral Secchi Disc Depths and Water Quality Measurements in Survey Area 13

LIST OF FIGURES

		Page
Figure 1.	Study Area	14
Figure 2.	(a) Transmission depth profiles at 532 nm for four selected locations (A to D)	15
	(b) Multi-spectral secchi disc depths at four locations (A to D)	15
Figure 3.	Normalized upwelling quanta irradiance spectra for four locations (A to D). + wavelength of LIDAR system ..	16
Figure 4.	(a) Spectral reflectance for different intertidal and beach material under diffuse sky conditions	17
	(b) Spectral reflectance for different intertidal and beach material under clear sky conditions	18
Figure 5.	Variations of spectral irradiance ratio with sediment concentration and bottom depth	19
	(a) x Bottom depth greater than secchi disc depth with mean value of 2.4 ±0.9 times secchi disc depth.	
	(b) Bottom depth less than secchi disc depth.	
	Bottom types: S-sand, M-mud, R-rock.	
Figure 6.	(a) Ratio of upwelling spectra (530/620) for similar suspended sediment concentrations but different bottom contributions	20
	(b) Ratio of upwelling spectra (530/620) for different suspended sediment concentrations and no bottom contributions	20

INTRODUCTION

Aerial photography and remote sensing multi-spectral scanning techniques can be used to provide information on bottom composition and water depths in shallow areas. The reflectance signal in shallow waters is a function of the optical properties of the water column, the depth of water and bottom type. Atmospheric, sea surface and instrumentation (e.g. scan angle) effects will distort the signal received by an above surface sensor. At a sub-surface level the bottom reflectance signal is modified by the spectral properties (absorption and scattering) of the water column. If two of the three properties (water depth, bottom type, or optical water properties) are known then the third property can be considered. If the optical water properties of an area are homogeneous and bottom reflectance spectra have the same shape then water depth information can be extracted by ratio algorithms from multispectral scanner data, Lyzenga (1978). If bottom reflectance is homogenous over a given area then a ratio of optical water attenuation coefficients can be extracted from a varying water depth regime, Lyzenga (1981). Lastly, with uniform optical water properties over a given area the variations in bottom reflectance and hence bottom type and composition have been determined by Lyzenga (1981).

Water depth variations are not easy to distinguish from bottom or water colour changes and so far the analysis of data by Lyzenga (1978, 1981) requires knowledge of or data (within the given scene) on the deep water (no bottom/depth effects) spectra.

FIELD LOCATION

The Canadian Hydrographic Service (C.H.S.) have been conducting a 3 year survey programme in a location on the southeast coast of Nova Scotia.

The area extended from Beaver Harbour to Liscomb Island (See Fig. 1). The bottom topography was complex with all bottom types, sand, mud, rock and vegetation being present in the area. The locality contained many small islands and shoals and was fed by two major river sources, the Moser River and Ecum Secum river, and several smaller rivers and streams. A remote sensing bathymetry evaluation programme was organised by the C.H.S. for this area. Simultaneously a small pilot project was undertaken by the Atlantic Oceanographic Laboratory (AOL) to determine.

(i) the optical water characteristics of the area

(ii) whether the in situ measurement techniques and analysis routines were suitable for the optical environment encountered.

(iii) whether bottom reflectance effects could be observed in the data set.

This last objective was to be undertaken by making optical measurements, in a uniformly homogeneous water mass, under increasing water depth conditions until a deep water reference station was established. For the duration of the project a Laser (LIDAR) bathymeter was flown from a CCRS-DC3 aircraft. CCRS personnel made in situ water attenuation measurements with a transmissometer modified to measure at 532 nm, the same wavelength as the Laser. A CCRS multi-spectral scanner also overflew the area during the only period of clear skies. CCRS personnel attempted measurements of atmospheric spectral attenuation. Optical measurements of the area were made by York University with a Biospherical 12 channel spectral irradiance meter and a Sea Tech operating at 660 nm. These measurements concentrated on absolute spectral attenuation coefficients, reflectance and water quality and as such were made during the few brief periods of clear blue skies. The work

presented in this text was unable to utilize absolute coefficients and concentrated on relative spectral changes due to water quality and bottom composition. This meant that water depth information could not be extracted from this data set.

DATA COLLECTION

Upwelling quanta spectra (400-720 nm) were measured at 1 m with a Techtum Quanta scanning spectra irradiance meter. There spectra were collected under varying sky conditions, mainly cloudy or overcast, without the benefit of sub-surface irradiance and each spectra was normalized to its maximum wavelength signal. This technique allows all ratio algorithms to be examined but forfeits all absolute information, in the case of depth determinations this normalization procedure actively destroys the most useful information. The wavelength at which the maximum signal occurs indicates the wavelength of maximum penetration of daylight and bottom spectral reflectance for shallow waters. The depth to which daylight can penetrate a given water mass determines the bathymetric depth that may be extracted from remote mesurements.

Water samples were collected at approximately 1m and later analyzed for suspended particulate matter, particulate organic carbon, salinity and total pigmented (chlorophyll *a* and phaeophytin) concentrations. Secchi disc measurements were made at each location with the depth of disappearance being measured through three different Kodak Wratten filters, a blue Wratten No. 98 filter, a green Wratten No. 99 filter and a red Wratten No. 29 filter.

In collecting the upwelling spectra a location had to be found in the test area where the water quality (as measured by the secchi disc) and bottom type (as measured by a lead line bottom sample) were uniform.

The test area was spasmodically sampled on the first day with a secchi disc to establish areas of optical uniformity. The second day these areas were examined in more detail to determine bottom composition. Potentially suitable sites were selected and upwelling measurements were made in water depths a) less than one secchi disc depth b) approximately twice the secchi disc depth c) three times or greater than the secchi disc depth, to act as the deep-water reference spectrum.

OBSERVATIONAL MEASUREMENTS

The strategy of collecting data at specific sites and depths was found to have practical limitations. Many of the shallow depths and bottom types were found close to the numerous small islands. As wind conditions changed over the survey some sites were affected by wind induced stirring altering the turbidity and hence optical properties. A line of stations conducted out from the lee of an island would find an increased water turbidity at the outer stations or if on the windward side a marked increase in turbidity, wave-action and hence operational difficulties in very shallow waters. Several locations near the harbours and river mouths were unable to provide a deep-water site at all for these "river" optical water type. One locality was found to be highly abundant in small (1"-2" size) jelly fish resulting in interference with the measurement of upwelling irradiance so that the station had to be abandoned.

In areas where deep channels existed on the bathymetric charts it was found that bottom type was not consistent with the shallow areas. Although the assumption was made that the deep water stations would not be feeling "bottom" it was desirable, where possible, to select the three depth sites with the same bottom type.

In the very shallow sites (less than the secchi disc depth and typically less than 5 m) some deductions concerning absolute optical properties could be made. It was found that spectral irradiance measurements throughout the water column at these sites did not necessarily decrease exponentially with depth. Reflection from the bottom, especially over sandy bottom types, was sufficient to offset depth affects over very small water depths (1-5 m). Also the affect of wave action on the value of upwelling irradiance just above the sea bed for these shallow sites became analogous to wave induced variations in downwelling irradiance just below the sea surface.

LOCAL OPTICAL CHARACTERISTICS

Some idea of the optical variability of the area can be obtained from the secchi disc values given in Table 1. The depth as seen through the green filter is maximum with minimum depth penetration through the red filter. However, there is a greater range of values in the blue measurements for Table 1 subdivisions (b) and (c) and almost as great a range as the green in division (a). The green portion of the spectrum has the maximum penetration and hence minimum water attenuation whereas the changes in the blue portion of the spectrum have traditionally been attributed to the changes in dissolved constituents in the water mass (Jerlov, 1968).

Figure 2a shows the depth attenuation profiles from the CCRS attenuance meter utilizing a 532 nm wavelength detector. Sites B, C, D (see Fig. 1) all show depth structure with the clearer water nearer the bottom but with a slight decrease in attenuance at bottom (this may be false since the meter 'hit' bottom on virtually all profiles). Profile A is from harbour waters and shows both a surface and bottom turbid layer. The

surface layer in the harbour (and hence river) mouth was discoloured a yellow brown indicating a strong organic absorption by dissolved substance (termed yellow substance, Jerlov, 1968) the secchi disc measurements for this station also showed a much stronger attenuation in the blue measurement (Fig. 2b). Figure 3 gives the four normalized upwelling profiles for the selected sites, these spectra were not collected at the same time(day) as the attenuation profiles and hence only general comparisons can be drawn. The wavelength (530 nm) of the Lidar sensor is also shown in Fig. 3 but only corresponds to a maximum in the upwelling signal for station D. Stations A to C all have maximal spectral upwelling between 550-580 nm. The spectra between 500-550 nm show marked variations for the different locations. In interpreting these spectra it must be remembered that they are in quanta units and hence biased towards the red end of the spectra. Similar spectra can be deduced from Jerlov's (1968) water types (note these are given in energy units) to show that spectra C & D are similar to coastal water types 5 and 1. Spectra B and A do not represent more turbid coastal water types (characterized by a greater shift towards the red) but water masses with a depleted blue portion of the spectrum and a small resulting shift in the spectral maxima.

WATER QUALITY AND BOTTOM TYPE

The secchi disc measurements in Table 1 all indicate that variations in the water quality (content) can be expected in the survey area. There variations will have to be extracted from the spectra if bottom characteristics are to be examined. Since absolute values have been lost by the normalization process a suitable ratio must be found. This ratio will of necessity be the ratio which maximizes the spectral changes with water

quality, unlike the ratios utilized by Lyzenga (1978) which where required to remain relatively constant with water quality changes.

The total pigmented content could be related to the suspended load measured in the survey area with a correlation coefficient of 0.60 (significant at a 99% level) but did not show any consistent relationships to the in situ optical properties (cf. Topliss, 1982) or bottom types. Analysis of previous spectra from Nova Scotia inshore waters had showed that a 530 to 570 ratio was optimum for showing both variations in suspended load and variations in dissolved organic composition. Since 570 nm is approximately the spectral wavelength of the maxima signal, this ratio would represent variations in the blue to maximum portions of the spectrum.

In order to determine the potential effect of the sea bed on the upwelling spectra however the spectral reflectance signal of the different bottom types must be determined. Beach and inter-tidal material was selected as a means of estimating reflectance of bottom types. Not all types were available at any given site and two locations, Conrad Beach and Minas Basin, were selected in order to obtain a full range of types. Figure 4a shows the insitu spectral reflectance measured under totally diffuse conditions, for sand, gravel, dark mud and two types of vegetation. Figure 4b shows similar spectra for mud, gravel and two types of vegetation measured under clear sky conditions. Instrumentation shading and differing atmospheric conditions prevent comparison of absolute reflectance values between the two figures. The important feature is that both the sand and mud (and to a lesser extent the black mud) show increasing spectral reflectance towards the red end of the spectrum. Figures 4a & 4b are in agreement with the spectral shifts observed by Lyzenga (1978) for sand, mud and green vegetation. Lyzenga (1978) noted that bottom materials with

similarly shaped reflectance spectra (such as sand and mud) cannot easily be distinguished since they have nearly equal reflectance ratios. If a bottom reflectance contribution is present in the upwelling spectra then it should, according to, Lyzenga (1978) cause a shift in ratio algorithms producing a parallel line for points "feeling bottom". The selection of a suitable ratio of wavelengths at which this affect can be maximized will depend on the water quality properties. In order to utilize both the blue and red portions of the spectrum (and hence observe any bottom shift) a 530/620 ratio was used and is shown in Fig. 5. Only a small number of data points is available and in general falls into two lines, those for spectra collected in water depths less than their respective blue secchi disc depth and those that do not "see" bottom. One bottom point lies nearest to the water quality curve and one water quality point, taken from Ecum Secum Harbour, lies with the "bottom" points. The effect of depressing the blue end of the spectrum and increasing scatter in the red (from river discharge) have the same affects on this ratio algorithm as a contribution from bottom reflectance. Only one set of points were taken under a situation that approached the original data collection strategy. All three points were from White Island, taken in clear water with approximately the same suspended load at each site for a varying depth of water column and a consistent sandy bottom. By ratioing the deep water and shallow water spectra (differences cannot be obtained after normalization) the resulting spectral difference can be shown in Fig. 6a. The linear proportion of the curve is short due to the limited sensitivity of the recording system (see error section) but indicates a differential shift towards the red due to the addition of bottom reflectance for the shallow station. Figure 6b gives the spectral ratio for two normalized upwelling spectra taken at the

same stations (Round Island and Barren Island) not "seeing" bottom, but with very different suspended sediment loads. The two affects of changes in suspended material and "feeling" bottom cannot be distinguished by simple ratio algorithms.

ERRORS OF MEASUREMENTS

This experiment was only considered a pilot project with one of the aims being to determine whether the measurement techniques and analysis routines were suitable for the optical environment. The errors on measurements would depend largely on the optical properties that would be found in the area, unknown prior to the pilot project. The resulting survey showed that all forms of the measurements and analysis routines were being pushed to the limits of their applicability and as such the scientific quality of the results are extremely limited.

Suspended sediment concentrations were low, typically 2-0.5 mg/l. This puts the actual gravimetric method at the edge of its suitability with small (1 litre and less) volumes of water. The particulate organic carbon analysis produced low values with very high blanks. The blank samples extended the full range of the measured values making the data unusable. There was evidence in the test area of a strong influence of dissolved organic material. Such dissolved contribution is usually monitored insitu or in the laboratory by ultra violet absorption methods not available to the author. The use of small crafts meant that large volumes of water could not be easily sampled either for surface or depth measurements. The lower the concentration of material the greater the penetration of light and hence the greater importance of any depth stratification. The area was found, by separate survey, to be stratified and no consideration

of the varying water column is considered in this brief analysis. However it should be noted that the greatest contribution to the upwelling light signal still comes from the surface few metres, the contribution of the water column being weighted by an exponential function. Differences between surface stations were large and hence the gross optical features were still determined by the surface water samples.

The sensitivity of the instrumentation was also a severe limiting factor in making these measurements. The output was an analogue graphic recorder which can only record a linear output over a given sensitivity range. This means that the low output in the 400-500 nm and 600-700 nm portion of the spectrum is being lost by reduction and is of limited value. This resulted in anamolous ratios in Fig. 6a & b where one of the signals in this wavelength range is effectively being recorded as close to zero.

The last error or limitation of the programme was the fact that only one scanning light meter was available meaning that variations in surface illumination could not be extracted. The loss of absolute values meant that the water depth affect could not be considered and the necessarily normalization procedure meant that the maximum signal and hence maximum penetration of the water column was being lost.

CONCLUSIONS

The pilot project was successful in that a limited effect of bottom composition was seen in the water optical measurements. The bottom composition of mud or sand could not be distinguished as anticipated by Lyzenga (1978). A colour shift in the upwelling spectra was produced by "seeing" bottom but this effect could not be distinguished by ratio techniques from the effects of water colour charges. Absolute values may have helped to

differentiate between these two situations for known water depths.

The survey area was observed to have visible colour changes in optical properties. The harbour/river waters were notably clear yellowy-brown, the water around the inner islands was a bluish-green, often opaque or milky, whereas the colour of water around the outer islands was a clear greenish-blue. These colour changes corresponded to a wide range of secchi disc penetration depths, but a still relatively small dynamic range of material concentration (cf. Table 1). The highly variable blue portion of the optical measurements indicated the importance of the dissolved organic contribution on the light field, which was not measured here, but will be pronounced at the LIDAR, operational wavelength and must be considered in any thorough understanding of the underwater light field.

Possibly the most important conclusion of this survey showed the area around Liscomb was similar in optical characteristics to many regions of Nova Scotia (Topliss, 1982) which have a sparsely populated coastline, organic river discharges, low suspended load and relatively low biological content.

RECOMMENDATIONS

1. The optical properties of the test area were not known prior to the pilot study. The area was neither horizontally nor vertically optically homogeneous and hence represented an extremely complex case for current bathymetric measurement by remote sensing methods. The percentage and location of Canadian waters suitable for bathymetric charting by remote methods needs to be identified. This task could be started by making secchi disc measurements (with spectral filters) a routine part of CHS surveys.

2. The test site indicated that dissolved organic river materials were influencing the blue end of the underwater light spectrum, especially at the Lidar wavelength. Since the test area was considered optically typical of shallow coastal areas around Nova Scotia (and regions similar in geochemistry to Nova Scotia) this problem can be expected to re-occur for many remote applications of bathymetry on the east coast of Canada. Expertise and technology needs to be established within Canada to address this research problem which, although not unique (similar optical conditions occur off Scandanavian coastlines) may be typical of Canadian waters.

3. Optical equipment available for monitoring inshore waters was not ideally suited to small boat operation. Many potentially useful devices require either mains power supplies and/or digital logging systems integrated into large ship board systems. Portability and use in an inshore (small boat) environment should be considered a useful feature in any future acquisition or development of optical remote sensing verification systems.

a: All measurements

	Maximum	Minimum	Range	Units
Blue filter	9.5	2.0	7.5	m
Green filter	11.0	2.75	8.25	m
Red filter	6.5	1.75	4.75	m
S.S.C.	4.67	0.48	4.19	mg L^{-1}
Tot. Pig.	2.40	0.20	2.20	µg L^{-1}
Salinity	30.89	22.44	8.45	°/°°

b: Measurements corresponding to upwelling irradiance sites

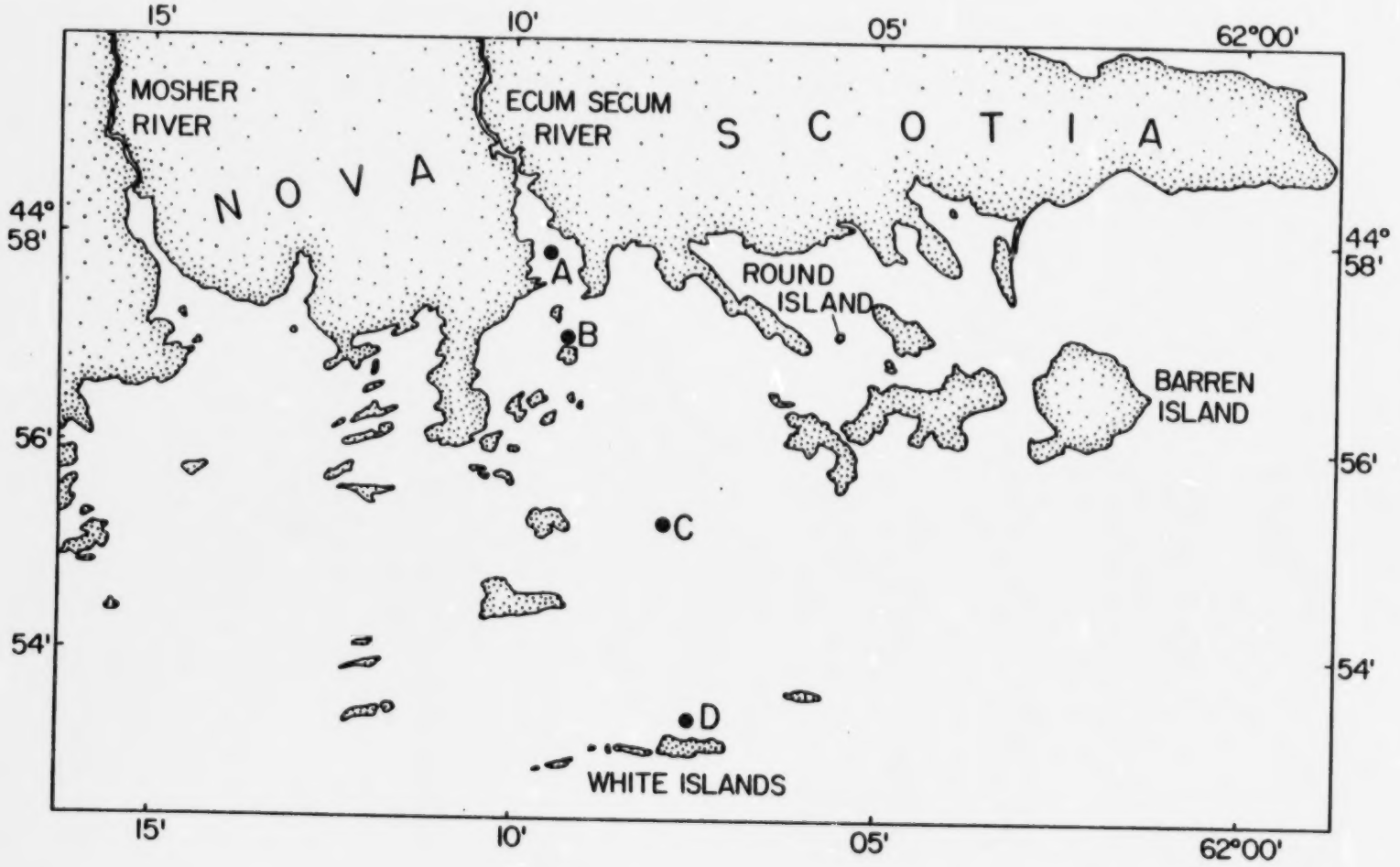
	Maximum	Minimum	Range	Units
Blue filter	9.5	2.5	7.0	m
Green filter	11.0	5.0	6.0	m
Red filter	6.5	3.5	3.0	m
S.S.C.	1.45	0.48	0.97	mg L^{-1}
Tot. Pig.	1.79	0.20	1.59	µg L^{-1}
Salinity	30.89	29.44	1.48	°/°°

c: Measurements excluding Harbour values and outer Islands

	Maximum	Minimum	Range	Units
Blue filter	7.5	2.5	5.0	m
Green filter	9.0	4.5	4.5	m
Red filter	5.5	3.0	2.5	m
S.S.C.	1.95	0.49	1.46	mg L^{-1}
Tot. Pig.	1.70	0.55	1.15	µg L^{-1}
Salinity	30.89	29.75	1.14	°/°°

SSC = Suspended solid concentration
Tot. Pig. = total pigments

Table 1: Spectral secchi disc depths and water quality measurements in survey area.



· STUDY AREA ·

Figure 1.

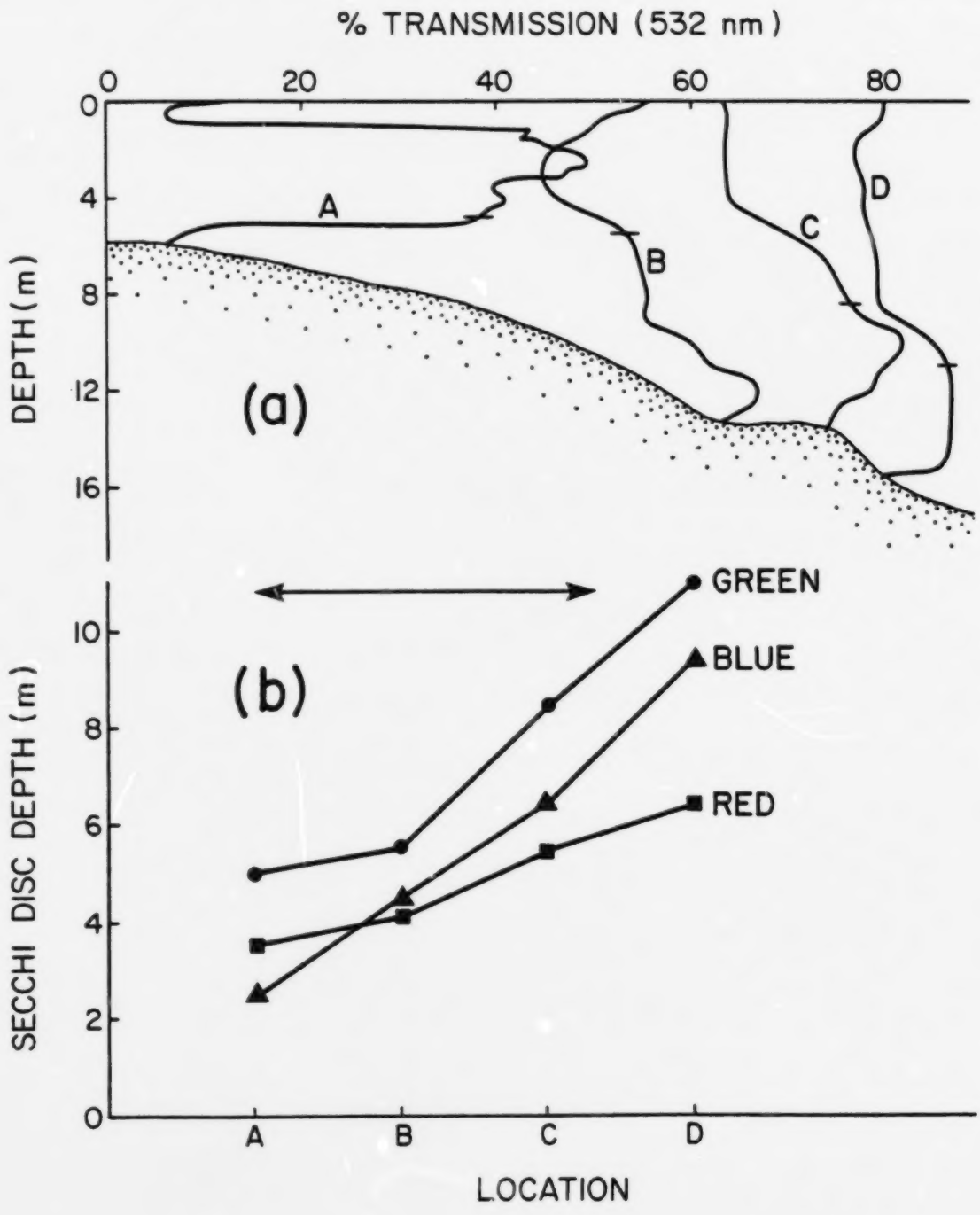


Figure 2. (a) Transmission depth profiles at 532 nm for four selected locations (a to D).

(b) Multi-spectral secchi disc depths at four locations (A to D).

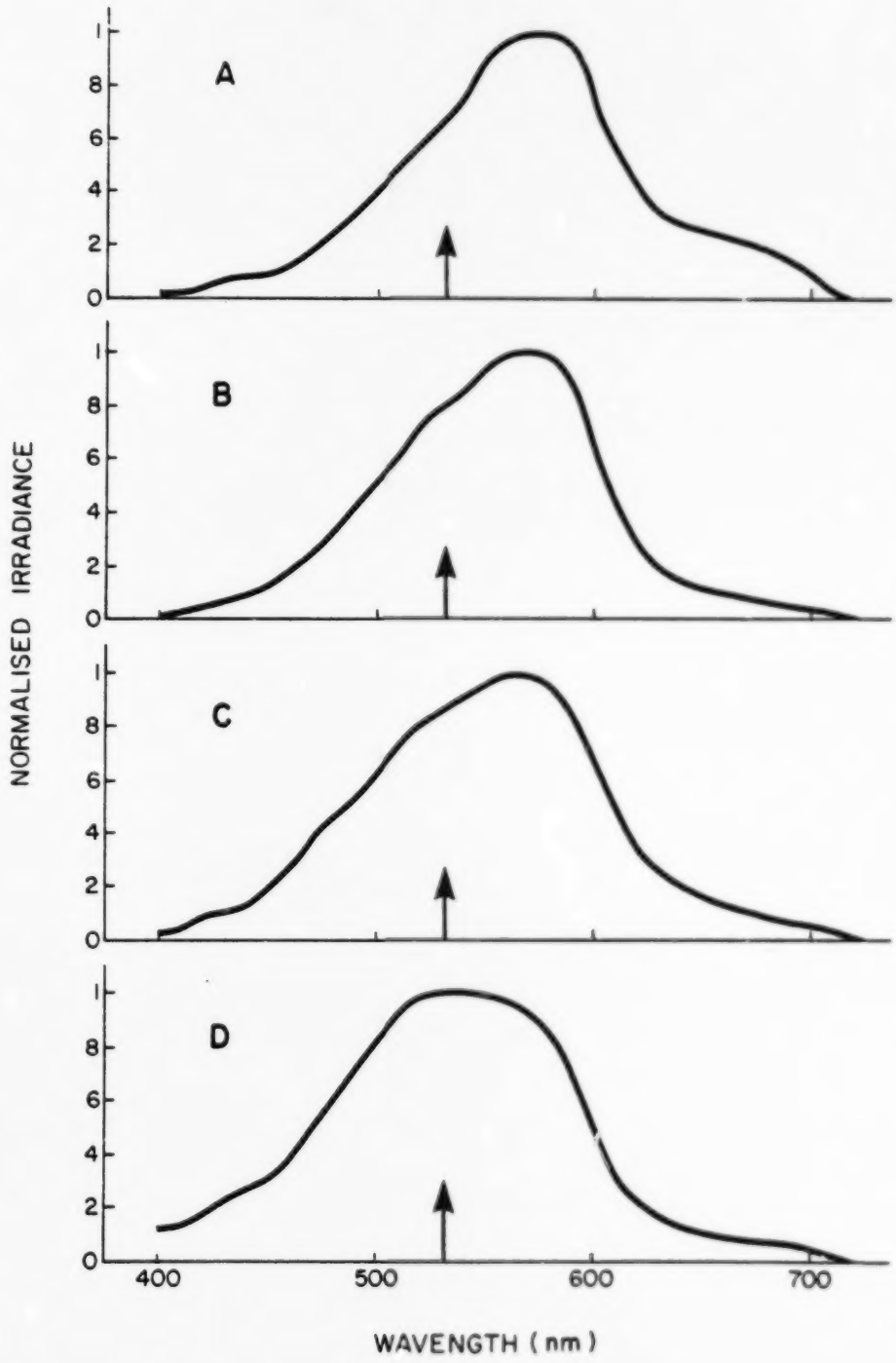


Figure 3. Normalized upwelling quanta irradiance spectra for four locations (A to D). wavelength of LIDAR system,

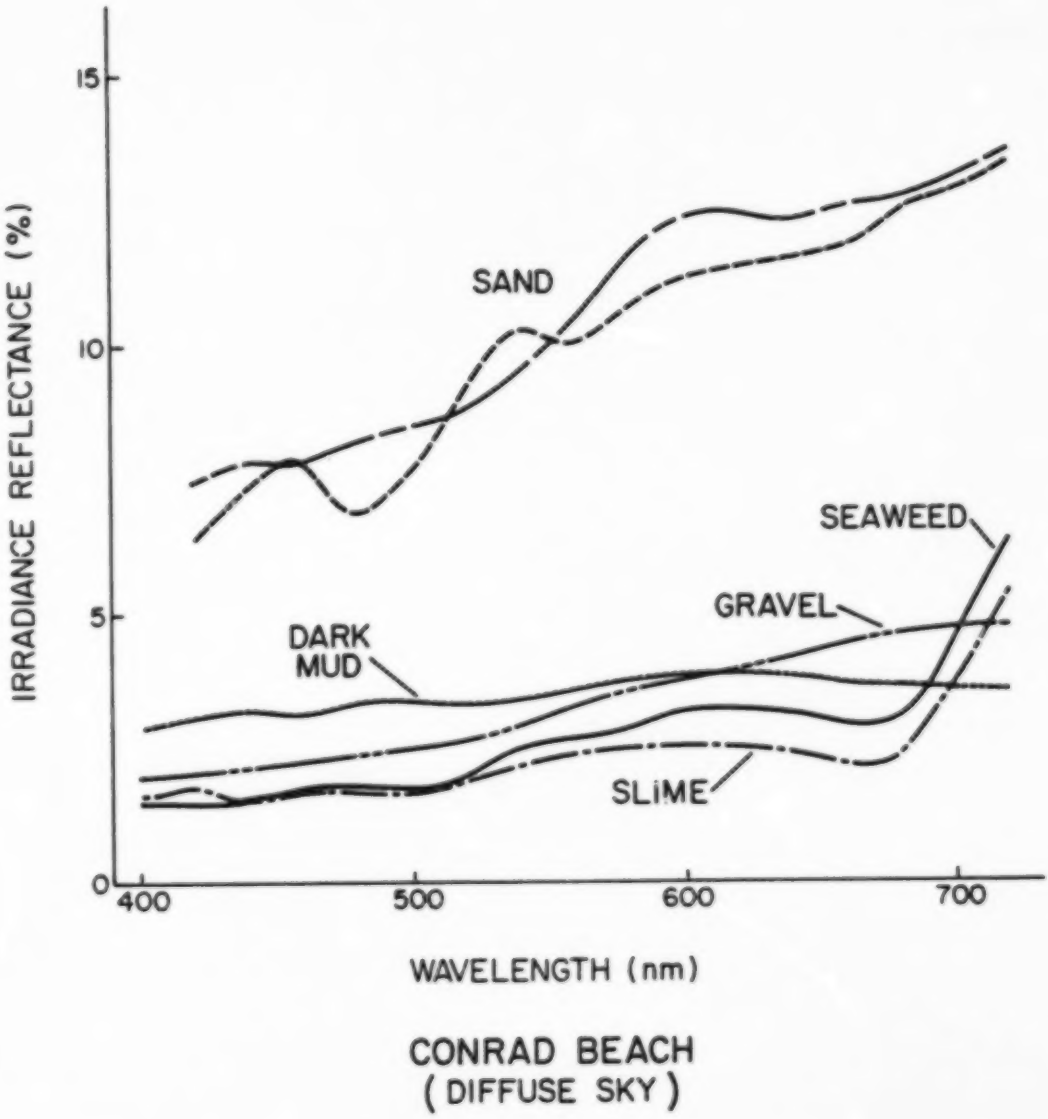


Figure 4. (a) Spectral reflectance for different intertidal and beach material under diffuse sky conditions.

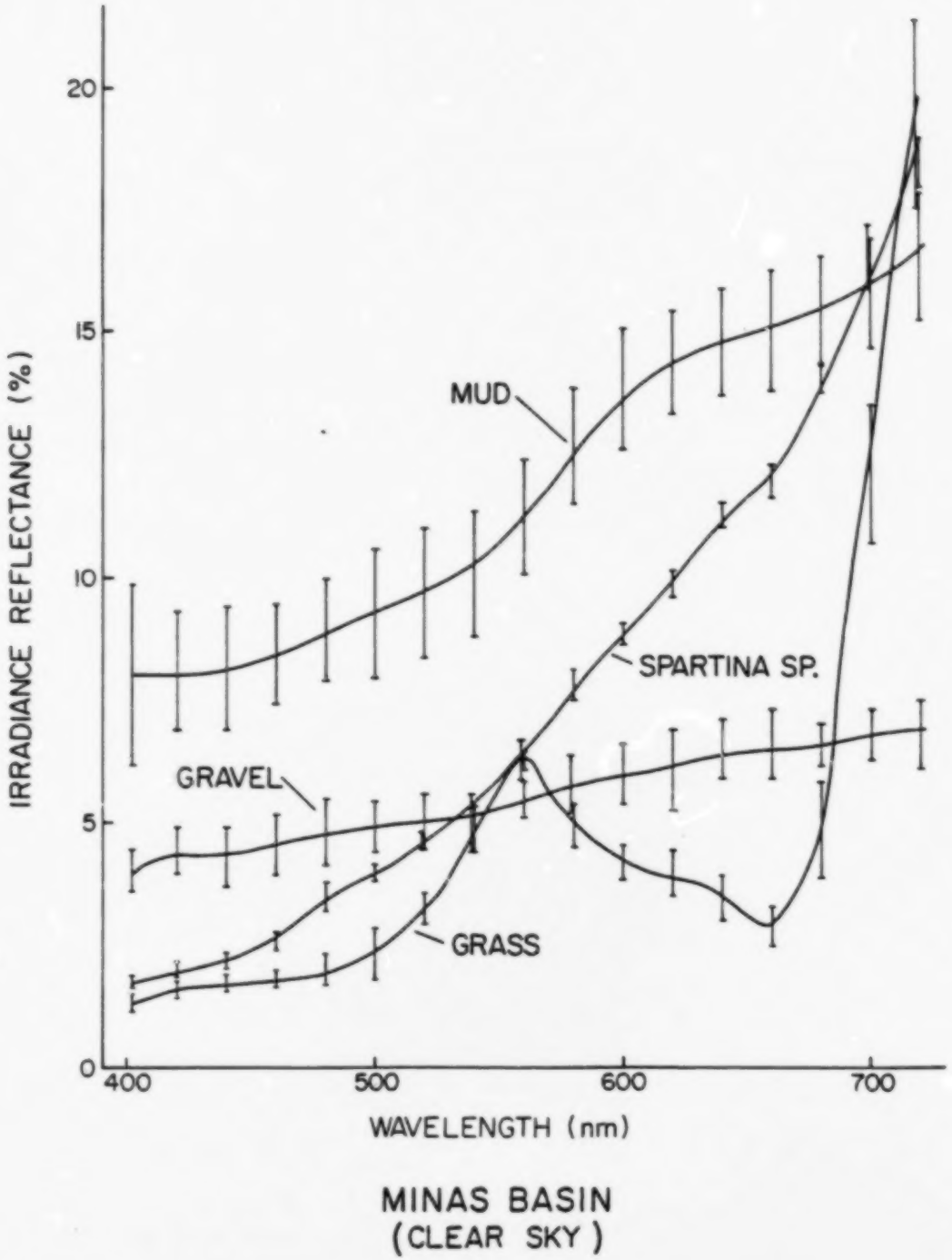


Figure 4. (b) Spectral reflectance for different intertidal and beach material under clear sky conditions.

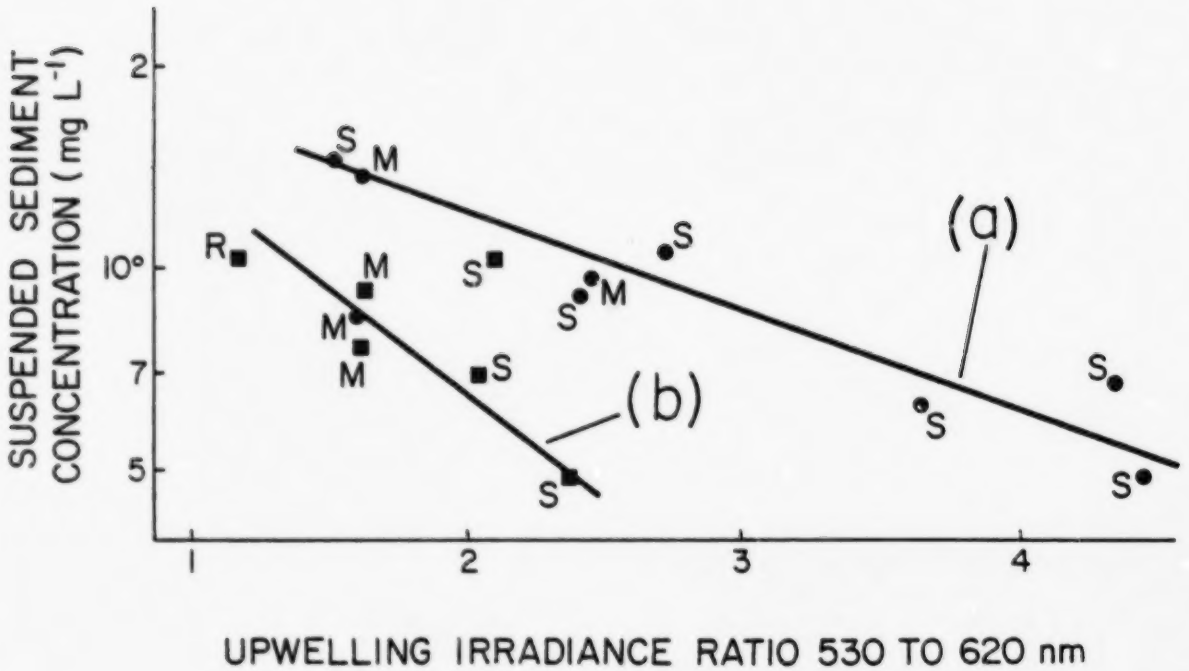


Figure 5. Variations of spectral irradiance ratio with sediment concentration and bottom depth.

(a) Bottom depth greater than secchi disc depth with mean value of 2.4 ± 0.9 times secchi disc depth.

(b) Bottom depth less than secchi disc depth.

Bottom types: S-sand, M-mud, R-rock.

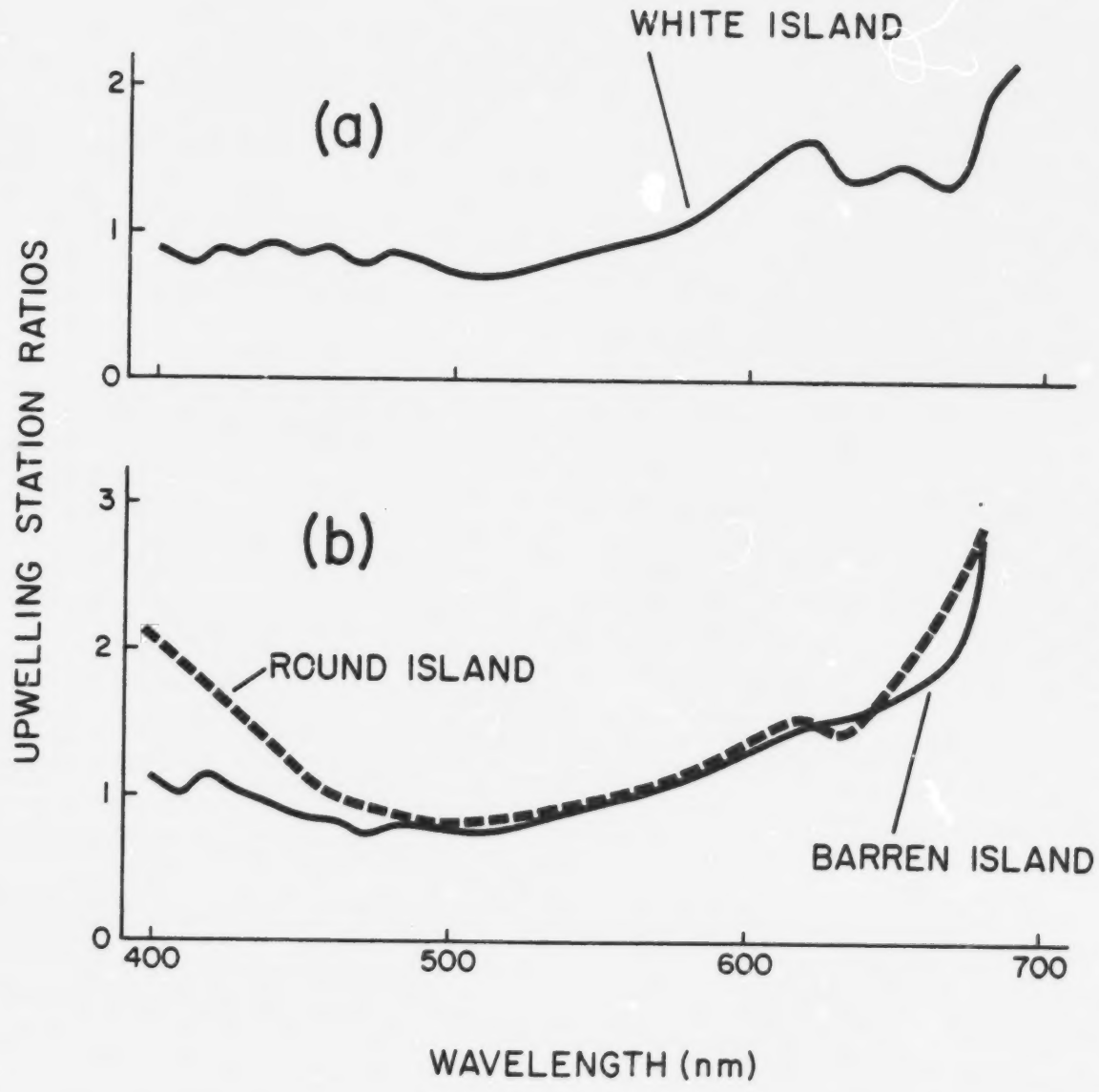


Figure 6. (a) Ratio of upwelling spectra (530/620) for simialr suspended sediment concentrations but different bottom contributions. (b) Ratio of upwelling spectra (530/620) for different suspended sediment concentrations and no bottom contributions.

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